Perseus in Sicily: From Black Hole to Cluster Outskirts
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Why only a small fraction of quasars are radio loud?

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Abstract. It is still a mystery why only a small fraction of quasars contain relativistic jets. A strong magnetic field is a necessary ingredient for jet formation. Gas falls from the Bondi radius $R_{\rm B}$ nearly freely to the circularization radius $R_{\rm c}$, and a thin accretion disk is formed within $R_{\rm c}$. We suggest that the external weak magnetic field threading interstellar medium is substantially enhanced in this region, and the magnetic field at $R_{\rm c}$ can be sufficiently strong to drive outflows from the disk if the angular velocity of the gas is low at $R_{\rm B}$. In this case, the magnetic field is efficiently dragged in the disk, because most angular momentum of the disk is removed by the outflows that lead to a significantly high radial velocity. The strong magnetic field formed in this way may accelerate jets in the region near the black hole, either by the Blandford-Payne or/and Blandford-Znajek mechanisms. If the angular velocity of the circumnuclear gas is low, the field advection in the thin disk is inefficient, and it will appear as a radio-quiet (RQ) quasar.

Keywords. accretion, accretion disks, magnetic fields, galaxies: active, galaxies: jets

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1. Introduction

Only a small fraction (about one tenth) of quasars exhibit relativistic jets, while their appearance is quite similar to the radio-quiet (RQ) counterparts in almost all wavebands except radio wavebands. The Blandford-Znajek (BZ) and Blandford-Payne (BP) mechanisms are the most favored models of jet formation in quasars (Blandford & Znajek 1977; Blandford & Payne 1982). Although we do not know which mechanism is dominant in the jet formation of quasars, a strong large-scale magnetic field near the black hole is necessary for the jet formation in radio-loud (RL) quasars either with the BP or BZ mechanisms. Strong magnetic field is probably a crucial factor causing the radio dichotomy in quasars (Sikora & Begelman 2013), though the black hole spin may also play an important role in the BZ scenario.

The external weak large-scale poloidal field (e.g., the field threading the interstellar medium) is suggested to be dragged inward by the accretion plasma, which is balanced by the magnetic diffusion in the disk for a steady field case. It was found that the field can hardly be dragged inwards by a thin disk ($H/R \ll 1$) because of its small radial velocity (Lubow *et al.* 1994). In order to solve this problem, Cao & Spruit (2013) suggested that the most angular momentum of the gas in the thin disk can be removed by the magnetically driven outflows, and the radial velocity of the disk is significantly increased. In this case, the external field can be advected efficiently in the thin disk with magnetic outflows.

2. Model

The gas falls almost freely toward the black hole, if the angular momentum of the gas is significantly lower than the Keplerian value at the Bondi radius. The angular momentum of the gas is roughly conserved until it approaches the circularization radius (e.g., Melia *et al.* 2001). The external weak magnetic field is dragged in by the gas in the region between the Bondi radius and the circularization radius, due to the field flux freezing, and the field threading the gas is substantially enhanced at the circularization radius. An optically thick, geometrically thin accretion disk is formed with the circularization radius, if the gas is supplied at an appropriate rate.

The radial velocity of the disk is significantly increased due to the presence of the outflows, if the angular momentum of the disk is removed predominantly by the magnetically driven outflows (see Cao & Spruit 2013). The field in such a disk with outflows is therefore efficiently advected toward the black hole. The strong magnetic field formed in this way may accelerate relativistic jets in the inner region of the disk near the black hole, either by the BP or/and BZ mechanisms. The object containing such an accretion disk with magnetic outflows may appear as an RL quasar, otherwise, it may be an RQ quasar.

The radial velocity of an accretion disk with magnetic outflows is assumed to be $1+f_{\rm m}$ times of that of a conventional turbulent disk. There is a minimal field strength required to maintain such a disk-outflow system, and we can therefore derive a necessary condition for RL quasars as

$$\tilde{\Omega}_{\rm B} < 0.336\left(1+\frac{1}{f_{\rm m}}\right)^{1/3}\times\left(\frac{T_{\rm B}}{\rm keV}\right)^{-5/6}\left(\frac{B_{\rm ext}}{\rm mGauss}\right)^{2/3}\left(\frac{M_{\rm bh}}{10^8 M_\odot}\right)^{1/3}\dot{m}^{-1/3}, \tag{2.1}$$

where $T_{\rm B}$ is the temperature of the gas at the Bondi radius, and $\dot{m}$ is the mass accretion rate in unit of Eddington value (see Cao 2016 for the detailed calculations).

The local structure of a disk accreting at a mass rate $\dot{M}$ with magnetically driven outflows, is the same as a standard thin disk accreting at $\dot{M}/(1+f_{\rm m})$. In the region beyond a critical radius $R_{\rm T}$, the disk may become a clumpy disk due to the gravitational instability. The accretion of the clumpy disk may be driven by the collisions of the clumpies. The large scale magnetic field threading the clumps may not be able to survive through repeatedly collisions. A clumpy disk region would be an obstacle for accumulation of external magnetic field. To avoid such a clumpy region in the disk, one requires $R_{\rm c} < R_{\rm T}$, i.e.,

$$\tilde{\Omega}_{\rm B} \le \left(\frac{R_{\rm T}}{R_{\rm B}}\right)^{1/2} = 0.0017 r_{\rm T}^{1/2}\left(\frac{kT_{\rm B}}{1~\rm keV}\right)^{1/2}, \tag{2.2}$$

where $r_{\rm T}=R_{\rm T}/R_{\rm S}$, and $R_{\rm S}=2GM_{\rm bh}/c^2$. This is the second condition for efficient field advection in an accretion disk with magnetic outflows Cao 2016).

3. Results and discussion

The external field can be efficiently advected in an accretion disk with magnetic outflows, only if the gas has angular velocity lower than both of these two critical values at the Bondi radius. In Figure 1, we plot the results varying with the black hole mass for different gas temperatures and external field strengths. It is found that the angular velocity $\Omega_{\rm B}$ is always required to be much lower than the Keplerian velocity, in order to form a strong field in the inner region of the disk. The results vary little with the mass accretion rate. The model parameter $f_{\rm m}=5$ is adopted in all the calculations. It guarantees the field to be significantly inclined to the disk surface, which is required for launching outflows from the disk.

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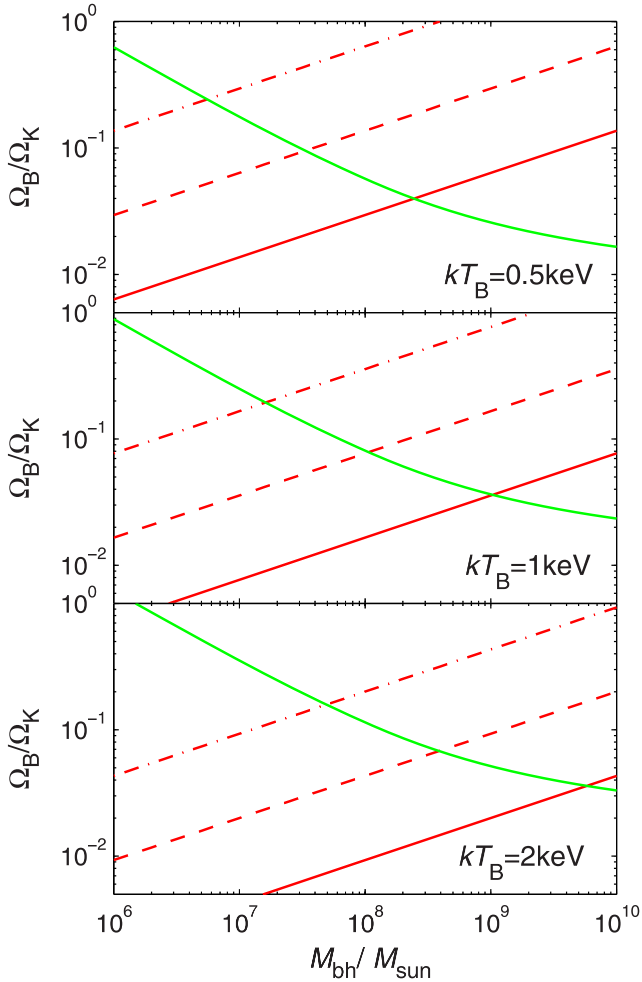

Figure 1. The critical angular velocities of the gas at the Bondi radius as functions of the black hole mass. The external field can be efficiently dragged in by an accretion disk with magnetic outflows only if the angular velocity of the gas is lower than both of the two critical values. All the calculations are carried out with $\dot{m} = 1$. The red lines correspond to the first condition (see Equation 2.1), and the green lines to the second condition for efficient field advection in the accretion disk with magnetic outflows (see Equation 2.2). The viscosity parameter $\alpha = 1$ is adopted in the calculations. The different types of the red lines indicate the results with different values of the external field strength at the Bondi radius (solid: 0.01 mGauss, dashed: 0.1 mGauss, and dash-dotted: 1 mGauss).

Typical magnetic field strengths of galaxy cluster atmospheres are at the order of $\sim \mu$Gauss, and the field strengths could be stronger for the ISM in galaxies. In the central region of our galaxy, the field strength of the gas can be as high as $\sim$mGauss. A weaker magnetic field requires the gas with a lower angular momentum at the Bondi radius for RL quasars, because the circularization radius decreases with decreasing angular momentum of the gas, which increases the amplification of the external magnetic field in the region between the Bondi radius and the circularization radius. Using *Chandra* X-ray observations of nine nearby radio galaxies, Allen *et al.* (2006) measured the temperatures of the gas at the Bondi radius of these galaxies, which are in the range of $\sim 0.5 - 1.3$ keV. We find that our main results are insensitive to the gas temperature (see Figure 1).

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The radio properties of AGNs are found to be linked to their host galaxies. It is found that the core galaxies invariably host a RL nucleus (Capetti & Balmaverde 2005). The core galaxies are slowly rotating and have boxy isophotes, while the power-law galaxies rotate rapidly and are disky. This supports the model suggested in this paper that the source accreting the gas with a low angular velocity may preferentially appear as an RL quasar. The mass accretion rate of an RL quasar is much higher than a conventional accretion disk with the same luminosity in an RQ quasar, because most of the gravitational energy released is carried away by the outflows (e.g., Li 2014). This implies that the mass growth of the black holes in RL AGNs is much faster than that in RQ AGNs with the same luminosity. This is consistent with the fact that the massive black holes in RL quasars are systematically a few times heavier than those in their RQ counterparts (Laor 2000).

4. Summary

The circumnuclear gas with a low angular velocity falls nearly freely from the Bondi radius to form an accretion disk within the circularization radius. The external magnetic field threading the gas is strongly amplified in this region due to the field flux freezing. For the gas with an angular velocity lower than a critical value, the field in the disk is strong enough to drive magnetic outflows, which carries away most of the angular momentum of the disk. This strongly increases the radial velocity of the disk, and therefore the field can be efficiently dragged inwards by the disk. Relativistic jets may be driven by such a large scale magnetic field through either the BP or BZ mechanism. In this case, the object may appear as an RL quasar.

If the angular velocity of the circumnuclei gas is larger than a critical value, the circularization radius (i.e., the outer radius of the disk) becomes larger, and the field cannot be amplified to a strong field in the disk to accelerate outflows. Thus, a conventional turbulence driven thin disk is formed within the circularization radius, and the advection of the field in the disk is rather inefficient. In this case, no relativistic jet is formed in the inner region of the disk, which corresponds to an RL quasar.

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